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RESEARCH MEMORANDUM

EXPLORATORY ENGINE TEST OF TRANSPIRATION-COOLED TURBINE-ROTOR BLADE WITH WIRE-CLOTH SHELL

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

Exploratory tests on a transpiration-cooled blade were made in a modified production turbojet engine to evaluate the blade design and the fabrication methods. The blade consisted of an internal load-carrying member, or strut, cast integrally with the base; for the twisted external surface of the blade, a permeable wire-cloth shell was attached to the strut. The investigation was conducted over a range of engine speed from 8000 to 11,500 rpm (blade-tip speed of 900 to 1300 ft/sec) and a range of coolant-flow ratio from 0.008 to 0.041.

Some damage, apparently due to fabrication methods, at the tip region of the trailing edge of the blades was noted after operation at a tip speed of 1300 feet per second. The damage apparently was not due to excessive temperature, but was caused by inadequate support of the shell in the damaged region. On other sections of the blades, the wire cloth did not appear greatly overheated, so that these results were considered satisfactory for the exploratory investigation of a transpiration-cooled rotor blade; and chordwise strut temperature distributions indicated that a satisfactory chordwise temperature distribution was provided by the orifices in the blade base. Spanwise temperature distributions and visual observations, however, indicated that better estimates and control of spanwise flow are needed.

INTRODUCTION

Up to the present time, experimental tests on air-cooling of gas-turbine blades in turbojet engines have dealt primarily with convection cooling (i.e., the coolant is forced through the hollow interior of the blades and discharged at the blade tip). Recently, experimental engine tests have also been conducted on transpiration-cooled turbine-rotor blades at the NACA Lewis laboratory to explore the heat-transfer characteristics and the problems associated with the application of this type of cooling to gas turbines. In transpiration cooling, the wall-temperature reduction is accomplished by forcing the coolant (air)

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through a porous blade wall, thereby forming an insulating layer of fluid between the wall and the gas stream. This cooling method indicates better effectiveness than other air-cooling methods such as convection cooling (ref. 1). Some problems pertinent to the application of transpiration cooling to gas-turbine blades are presented in reference 2.

As pointed out in reference 2, the amount of flow through the porous wall is dependent on the difference in the squares of the absolute pressure levels on opposite sides of the wall. Small changes in pressure level, therefore, can often result in large changes in coolant-flow rate. Methods for investigating pressure-level changes caused by chordwise pressure distribution and off-design operation of turbine blades are given in references 3 and 4. Prior to the actual application of transpiration cooling to turbine blades, porous materials are needed which are adaptable to conventional fabrication methods. For this purpose, a wire-cloth material was developed and the experimental variations between air flow and pressure drop were determined (refs. 5 and 6).

Previous discussions on transpiration cooling have emphasized the importance of the temperature of the porous material exposed to the hot gas flow. In the cooling of turbines, however, the blade can be designed wherein a shell is attached to a strut or load-carrying member so that the strut temperatures become more important for load-carrying potential than the shell temperatures. The shell must still maintain low enough temperatures to preclude serious oxidation and must possess adequate strength to withstand the forces imposed on a rotating blade. The strut, in conjunction with the porous shell, can be used to form compartments so that the cooling air can be metered by orifices in the blade base to obtain desired chordwise distribution of the coolant (ref. 3). Although experimental results have been obtained on shell-type transpiration-cooled stator blades fabricated from sintered materials (refs. 7 and 8), no published information is available for a rotating transpiration-cooled blade.

The present investigation was undertaken, therefore, to determine the adequacy of design and fabrication of a transpiration-cooled rotor blade operating in a turbojet engine. The principal items of interest in these exploratory tests were to determine: (a) if the orifices in the blade base provide proper chordwise distribution of the coolant, (b) whether the shell and its attachment to the strut would withstand rotational effects, (c) if proper spanwise distribution of the coolant would be obtained, and (d) strut temperatures and the effect of hot gas flow on the shell. Because these tests were made on a modified turbojet engine having both cooled and uncooled turbine blades, the effect of coolant emission on aerodynamic performance could not be determined.

For the blades investigated, the shells were fabricated from 20X200 mesh wire cloth and attached to an S-816 load-carrying strut member. Two such blades were installed in a modified turbojet engine that was operated to an engine speed of 11,500 rpm and to an effective gas temperature of 1350° F. Strut temperatures were obtained over a range of coolant-flow ratio (coolant-flow rate divided by gas-flow rate) from 0.008 to 0.041 at various engine speeds, and visual observations of the cooled blade shells were made after operation at various speeds.

BLADE DEVELOPMENT AND FABRICATION

The application of transpiration cooling to a complex structure such as a turbine blade presents many problems. It is shown in references 7 and 8 that the porous material must be thin enough to allow the cooling air to be brought into the narrow regions near the leading and trailing edges of the turbine blade. For turbine-rotor-blade application, the porous shell should also have adequate strength to withstand the imposed forces.

In the process of investigating materials that possess the characteristics of strength and sufficient thinness, a corduroy wire cloth was selected. Photographs of the cloth are shown in figure 1. It was found that by cold-rolling the wire cloth, a wide range of permeability could be obtained (refs. 5 and 6). The desired permeability of the porous material is dependent on the amount of air required to obtain sufficient cooling of the shell. The amount of air is, in turn, determined by the heat transfer through the wall. By using the analyses given in references 3 and 9, it is possible to determine a chordwise coolant-flow distribution required to maintain a constant prescribed wall temperature for a transpiration-cooled turbine blade.

For porous materials, the flow from the inner to the outer surface is a function of the difference of the squares of the pressure on opposite sides of the wall. Because of this dependency, investigation of the pressure distribution on the outside and inside of the blade is required. The general trends of the pressure distribution around the outside of a turbine blade can be obtained by use of the stream-filament theory (ref. 10).

Inside the blade, the coolant is subjected simultaneously to centrifugal forces, loss of flow, area change, heat addition, compressibility, and friction. A theory for this type of flow does not exist at the present time. Assumption can be made that the more influential effects act separately, thereby permitting estimates of the pressure variation of the coolant in the spanwise direction. This pressure, in conjunction with the pressure outside the blade, will determine the flow through the porous shell and the shell permeability.

Pressure variations around the periphery of the turbine blade at the midspan location are shown in figure 2. Because of differences in pressure drop available at various chordwise locations, it would be necessary to have a shell of varying permeability to meter the proper amount of air. This sort of design would probably suffice at one altitude but would result in overcooling at other altitudes (refs. 3 and 4). A method that affords the use of a constant chordwise permeability and also partially compensates for the effects of altitude is to provide different sized orifices in the blade base.

Figure 3 is a sketch of the transpiration-cooled blade developed for this investigation. The fins in the spanwise direction of the strut in conjunction with the porous shell form compartments for the cooling air fed through the orifices in the blade base. In addition to forming compartments for the coolant flow, the strut also lends itself for supporting a shell such as wire cloth or a sintered material lacking rigidity or strength. The orifices, by their different sizes, provide a different pressure inside each compartment. At the leading and trailing edges of the blades, the orifice diameters are 0.100 inch. The three orifices in the suction surface are 0.067 inch in diameter, and the three on the pressure surface are 0.047 inch. Although a pressure distribution such as shown in figure 2 exists around the blade, the use of orifices in the base permits a constant chordwise permeability of the shell, thus simplifying fabrication and providing the required coolant flow for constant shell temperatures in the chordwise direction. 3135

Figure 4 shows photographs of the components and assembly of the transpiration-cooled blade used in this investigation. The strut (fig. 4(a)), which is the load-supporting member, is cast from S-816 material, chosen because of its good casting qualities. The 20X200 mesh wire cloth of AISI type 304 stainless steel (unbrazed) was cold-rolled to 0.0205-inch-thickness reduction and formed to a shape similar to a standard turbojet-engine twisted rotor blade (fig. 4(b)). The permeability characteristics of the cloth with this thickness reduction (33.2 percent) are given in reference 6 (fig. 6(a)). The cloth was oriented so that the 20 wires were in the chordwise direction and the 200 wires were in the spanwise direction. After the wire cloth was formed, the tip and the trailing-edge sections were welded. The shell was then attached to the strut by spot-welding along the fins and at the base. Figure 4(c) is a photograph of a completed blade, and it shows the indentations at the strut-attachment points, which may affect the aerodynamic performance of the blade. As noted previously, no performance results were obtainable with the present apparatus. It is reasonable to expect, however, that improvements on the outside surface will be made as more experience is gained in fabrication of this type blade.

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APPARATUS AND INSTRUMENTATION

Engine

The modified turbojet engine used in this investigation was similar to that described in detail in references 11 and 12 except for a different configuration of the air-cooled blades. Throughout the investigation, standard twisted rotor blades were used adjacent to the air-cooled blades, as well as at all other locations on the turbine rotor. The two cooled blades were located diametrically opposite on the turbine rotor.

The instrumentation used on the engine was the same as that discussed in references 11 and 12 except for the location and number of thermocouples on the two cooled blades.

Instrumentation

In addition to the conventional instrumentation of the engine, chromel-alumel thermocouples were buried in the struts of the two cooled blades. Thermocouples 1, 2, and 3 (fig. 5) were located in the strut in the chordwise direction of the one blade, and thermocouples 4, 5, and 6 were located in the strut in the spanwise direction of the other blade. With this arrangement, a check on the temperatures of the two struts can be obtained by comparison of readings from thermocouples 2 and 5. A sample thermocouple installation can be seen in figure 4(a). Before the shell was placed over the strut, the groove holding the thermocouple was filled and faired smooth with high-temperature solder.

The measurement of the wire-cloth temperature is a difficult one even for a static test. The difficulties are due to the necessity of using small-diameter wires (possessing little strength) to minimize conduction and also of maintaining the thermocouple lead wires close to the porous surface so that the coolant flow through the porous material is not affected by the installation. Because of these problems, temperature readings of the wire-cloth shell were not obtained in this investigation.

TEST PROCEDURES

Strut temperatures were obtained for engine speeds of 8000 and 10,000 rpm and a rated speed of 11,500 rpm. Upon completion of each speed run, the condition of the shells was observed. The effective gas temperature ranged up to 1350° F. Coolant-flow ratios were determined by the strut-temperature limitation and by the required cooling-air pressure. At all times the coolant pressure measured at the hub of the turbine wheel was maintained at a higher value than the calculated relative stagnation pressure at the blade leading edge. (It was assumed that the pressure at the blade base was equal to the hub pressure.) This precaution was necessary to insure an outward flow through the porous shell and limited the minimum coolant-flow rate to 0.008. The maximum obtainable coolant flow was 0.041.

RESULTS AND DISCUSSION

In order to determine the adequacy of the design and the fabrication methods of the two transpiration-cooled blades, temperature distributions on the struts were obtained and the condition of the shells was observed. Average chordwise temperature distributions will be presented for engine speeds of 8000, 10,000, and 11,500 rpm. Local strut temperature distributions will only be shown for 10,000 rpm, since visual inspection revealed that the blades were damaged slightly after short-time operation at 11,500 rpm. Photographs of the blades after completion of the test will be given and discussed. 3135

Measured Temperature Distributions

Chordwise. - Average chordwise strut temperatures are plotted against coolant-flow ratio in figure 6. The temperature data are the arithmetic average of the three chordwise thermocouples at the leading-edge, midchord, and trailing-edge regions at the 3/8-span location from the base (fig. 5). This spanwise location was chosen since it should be in the region of the critical section for these cooled blades. The strut temperatures for the 8000 and 10,000 rpm yield about the same curve, while the few data points for the 11,500 rpm fall above the 8000- and 10,000-rpm curve.

Typical local strut temperatures along the chord at 3/8 span (fig. 5) for various coolant-flow ratios at 10,000 rpm are presented in figure 7(a). At the larger coolant-flow ratios, the leading- and trailing-edge temperatures are nearly the same, while the midchord temperature is slightly higher. At lower dilutions this trend reverses. In transpiration cooling of turbine blades, uniform chordwise temperatures should be obtained at design conditions only. The reversal in chordwise temperature distribution with decreasing coolant-flow ratio, therefore, is not unexpected. Temperature differences of magnitudes encountered at any flow rate (maximum of 100° F), however, would be considered small in the cooling of turbine blades. These relatively uniform strut temperatures could be an indication that satisfactory distribution of the coolant in the chordwise direction was accomplished.

Spanwise. - Spanwise strut temperature distributions for various coolant flows at an engine speed of 10,000 rpm are shown in figure 7(b).

These thermocouples are located on the strut as shown in figure 5. The rapid rise in strut temperatures from the 3/8 span to the tip signifies that the greatest portion of the coolant is discharged near the root section of the blade. Comparison of figures 7(a) and (b) shows that the midchord temperature in the spanwise group (thermocouple 5) is about 200° F lower than the midchord temperature in the chordwise group (thermocouple 2). These two thermocouples were located in identical locations but on different blades. From this inequality in temperature, it appears that the coolant-flow distribution to the two blades is unequal. Since only the total coolant flow to both of the blades could be measured, the particular flow rate to each blade is not known, so that the coolant-flow ratios given cannot be considered representative for either of the two blades tested. Although these results cannot be used to compare the cooling effectiveness of these blades with blades utilizing other cooling methods or configurations, they do give indications of the uniformity of cooling in both the spanwise and chordwise directions for the present blades.

Visual Observations

Visual inspection of the transpiration-cooled blades after engine operation at 11,500 rpm and an effective gas temperature of 1350° F showed that part of the wire cloth on the trailing edge of the tip region had been severed from the rest of the blade (fig. 8). When metal discoloration was used as an indication of maximum operating temperature, the wire-cloth shell did not appear greatly overheated in other regions. The pressure surfaces of both shells were hotter than the suction surfaces, as may be noted by the discoloration patterns shown in figures 8(b) and 9(b). Somewhat higher temperatures at the junction of the wire cloth and the strut than in the porous regions were also indicated. No evidence was apparent, however, of any separation in the band between the shell and the fins on the strut.

Although there are definite indications of spanwise variations in shell temperature, the orifices in the base of the strut seemed to provide satisfactory coolant distribution to minimize chordwise temperature variations (figs. 7(a), 8(a), and 9(a)).

The damage in the trailing-edge region was probably due to the fabrication methods. It is possible that the welding necessary to join the wire cloth may have induced brittleness in the wires in the neighborhood of the weld, so that some caution should be exercised in design and fabrication of this region. Perhaps the lack of sufficient rigidity could be alleviated by a shorter span from the strut support to the trailing edge of the shell.

CONCLUDING REMARKS

The following remarks may be made concerning the results of the investigation of the transpiration-cooled rotor blades:

1. These initial experiments were considered successful and indicate that a transpiration-cooled strut blade using a wire-cloth shell is feasible for temperature reduction of a turbine-rotor blade.

2. Satisfactory chordwise distribution of coolant flow is obtainable by the use of orifices in the blade base. 3135

3. The spanwise variations of shell and strut temperature indicate that better estimates of spanwise flow outside the blade and the development of adequate theories for the flow of coolant inside the blade are required.

4. Consideration should be given to strengthening the trailing-edge section of the blade where the shell was damaged during the high-speed engine test.

5. Studies on the aerodynamic performance and the effects of altitude and higher gas temperatures should be made for more effective application of transpiration cooling to turbine blades.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, November 24, 1953

REFERENCES

1. Eckert, E. R. G., and Livingood, John N. B.: Comparison of Effectiveness of Convection-, Transpiration-, and Film-Cooling Methods with Air as Coolant. NACA TN 3010, 1953.

2. Eckert, E. R. G., and Esgar, Jack B.: Survey of Advantages and Problems Associated with Transpiration Cooling and Film Cooling of Gas Turbine Blades. NACA RM E50K15, 1951.

3. Esgar, Jack B.: An Analytical Method for Evaluating Factors Affecting Application of Transpiration Cooling to Gas Turbine Blades. NACA RM E52G01, 1952.

4. Esgar, Jack B., and Richards, Hadley T.: Evaluation of Effects of Random Permeability Variations on Transpiration-Cooled Surfaces. NACA RM E53G16, 1953.

5. Eckert, E. R. G., Kinsler, Martin R., and Cochran, Reeves P.: Wire Cloth as Porous Material for Transpiration-Cooled Walls. NACA RM E51H23, 1951.

6. Donoughe, Patrick L., and McKinnon, Roy A.: Experimental Investigation of Air-Flow Uniformity and Pressure Level on Wire Cloth for Transpiration-Cooling Applications. NACA RM E52E16, 1952.

7. Bartoo, Edward R., Schafer, Louis J., Jr., and Richards, Hadley T.: Experimental Investigation of Coolant-Flow Characteristics of a Sintered Porous Turbine Blade. NACA RM E51K02, 1952.

8. Schafer, Louis J., Jr., Bartoo, Edward R., and Richards, Hadley T.: Experimental Investigation of the Heat-Transfer Characteristics of an Air-Cooled Sintered Porous Turbine Blade. NACA RM E51K08, 1952.

9. Livingood, John N. B., and Eckert, E. R. G.: Calculation of Transpiration-Cooled Gas-Turbine Blades. Trans. A.S.M.E., vol. 75, no. 7, Oct. 1953, pp. 1271-1278.

10. Huppert, M. C., and MacGregor, Charles: Comparison Between Predicted and Observed Performance of Gas-Turbine Stator Blade Designed for Free-Vortex Flow. NACA TN 1810, 1949.

11. Ellerbrock, Herman H., Jr., and Stepka, Francis S.: Experimental Investigation of Air-Cooled Turbine Blades in Turbojet Engine. I - Rotor Blades with 10 Tubes in Cooling-Air Passages. NACA RM E50I04, 1950.

12. Hickel, Robert O., and Ellerbrock, Herman H., Jr.: Experimental Investigation of Air-Cooled Turbine Blades in Turbojet Engine. II - Rotor Blades with 15 Fins in Cooling-Air Passages. NACA RM E50I14, 1950.

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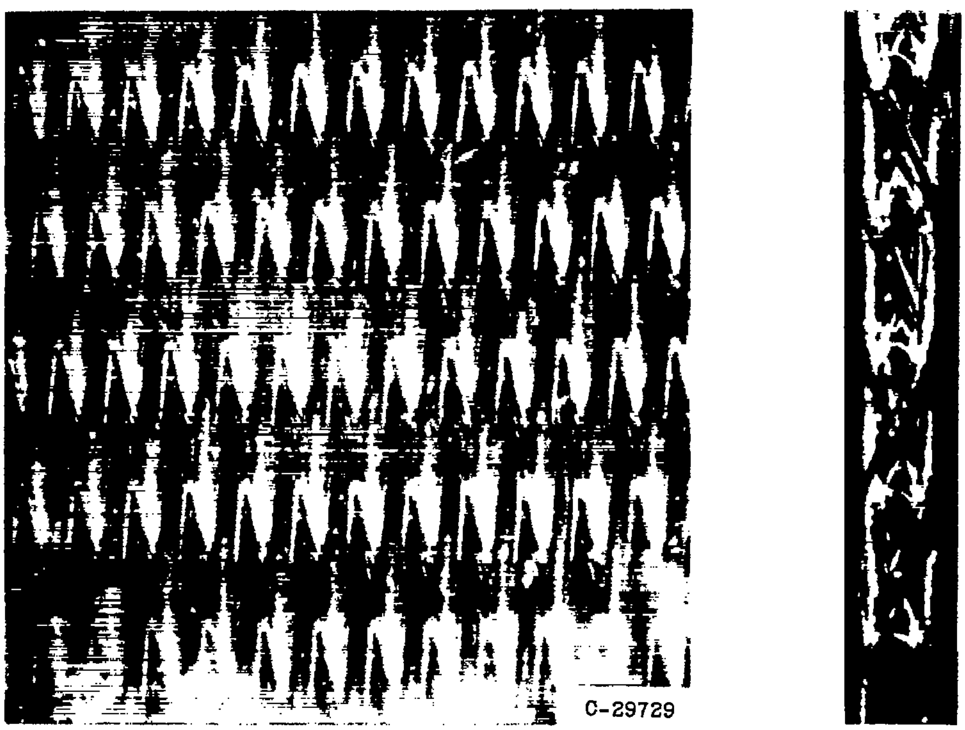

(a) Front view. (b) Side view.

Figure 1. - As-woven 20X200 mesh corduroy wire cloth (ref. 6).

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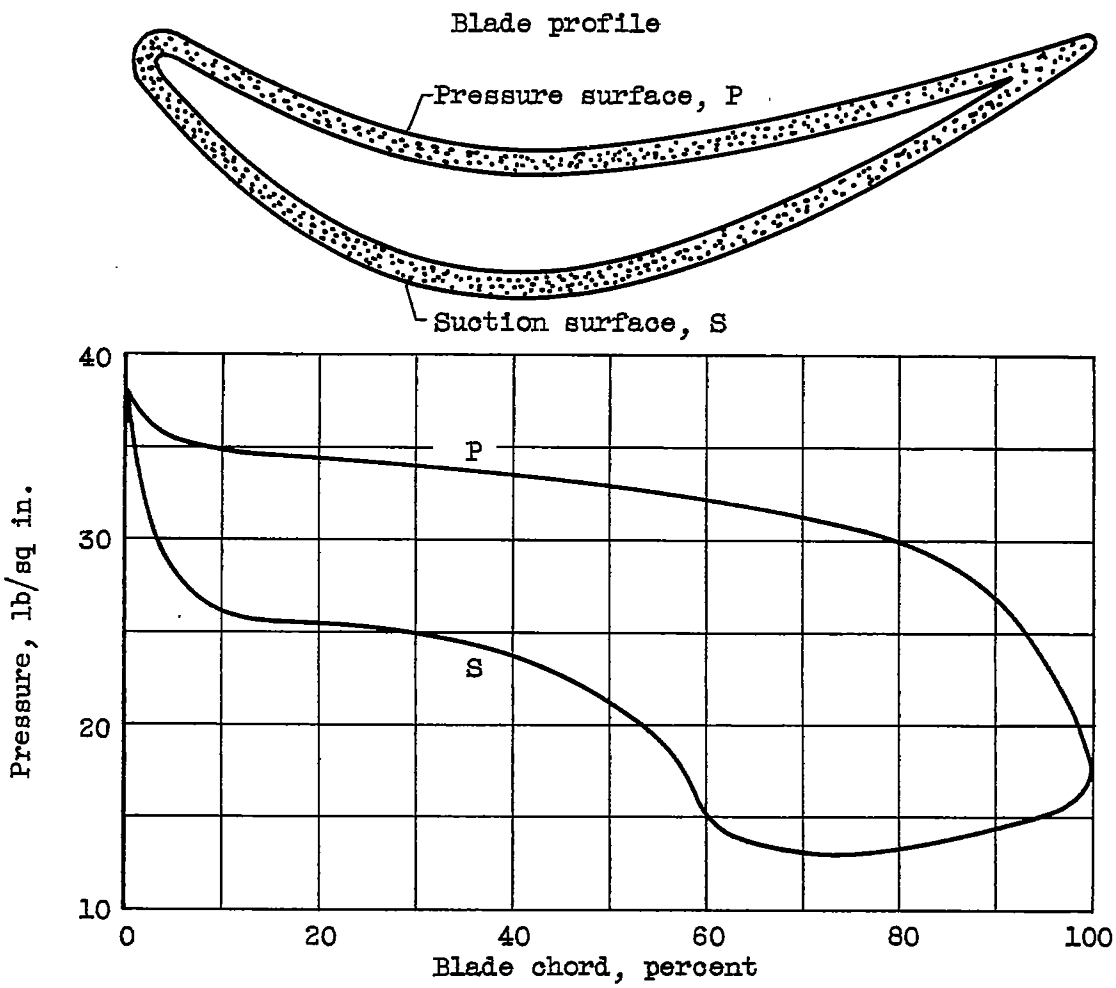

Figure 2 - Calculated pressure variations around periphery of rotor blade. (Sea level and 11,500 rpm.)

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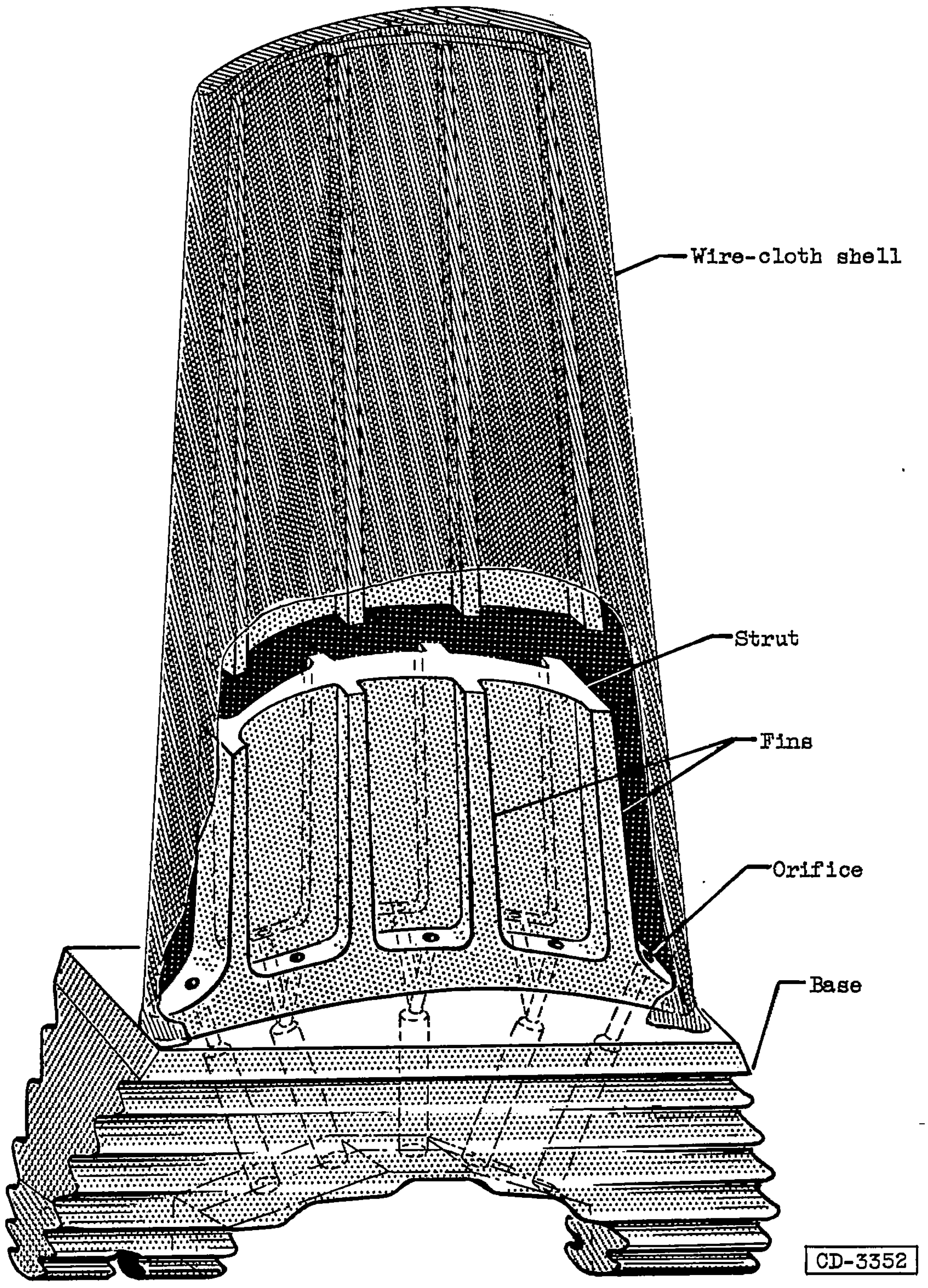

Figure 3. - Sketch of transpiration-cooled blade.

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(a) Strut. (b) Shell. (c) Assembly.

Figure 4. - Components of transpiration-cooled blade.

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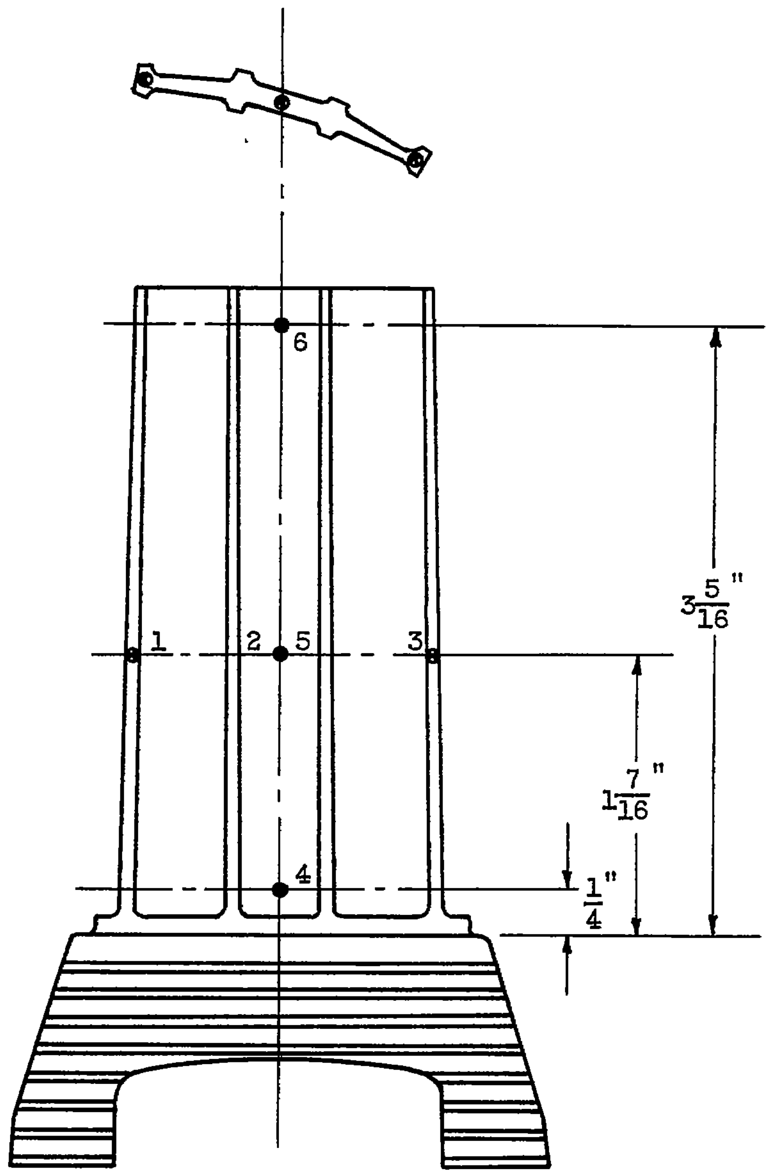


Figure 5. - Thermocouple locations for transpiration-cooled blades. (Thermocouples 1, 2, and 3 on blade 1 and thermocouples 4, 5, and 6 on blade 2.)

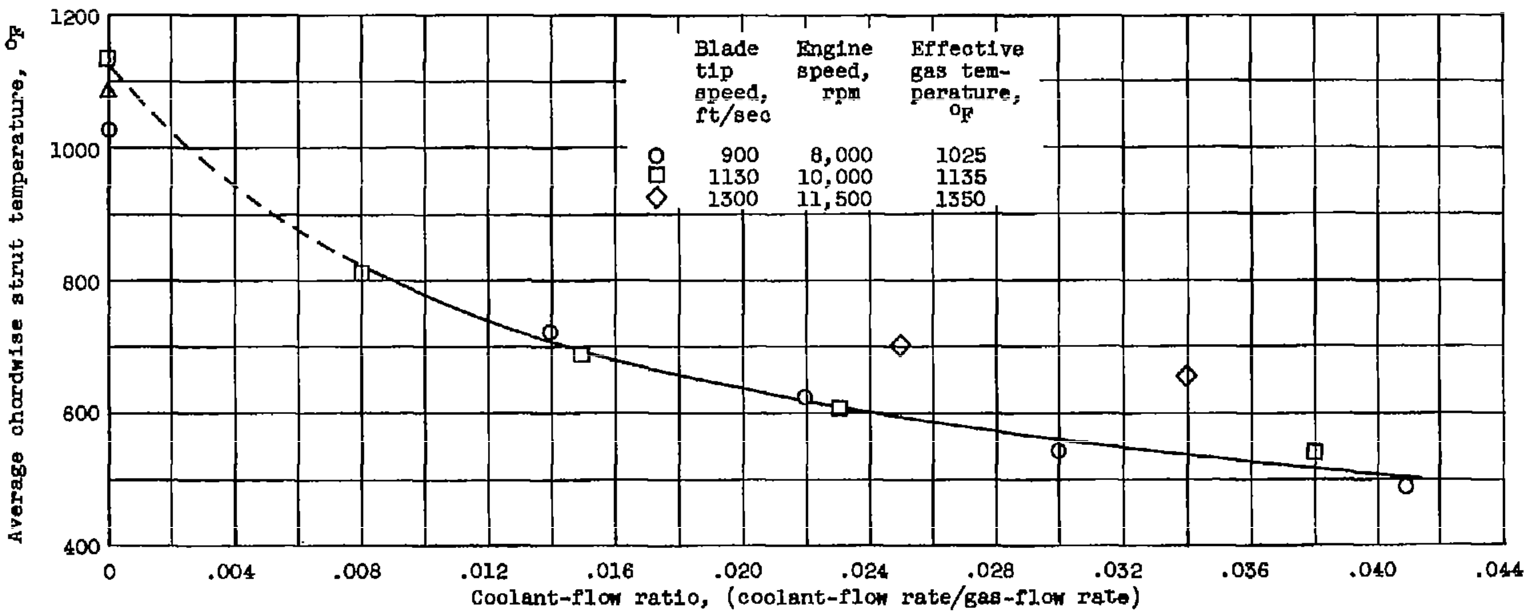
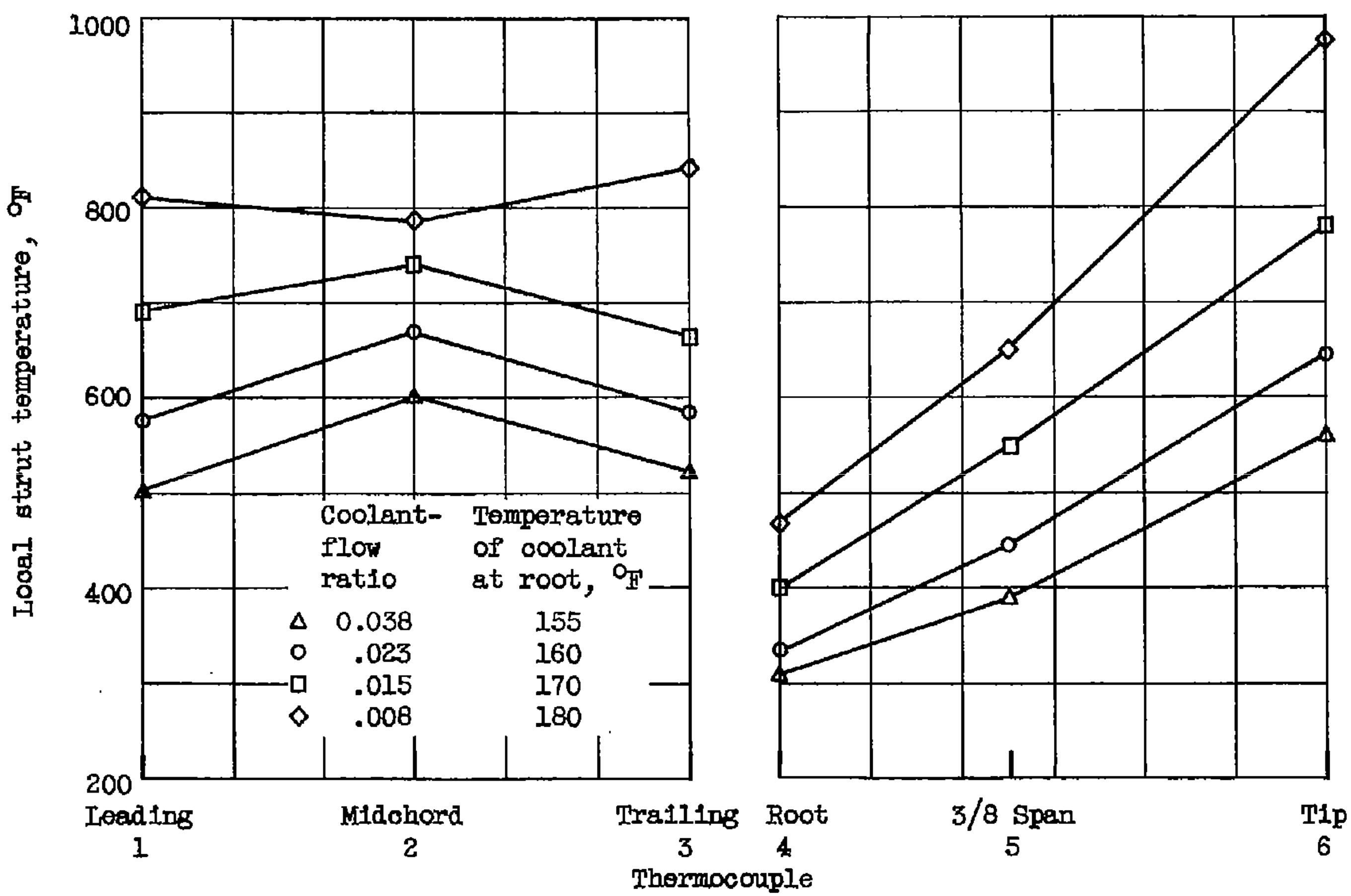


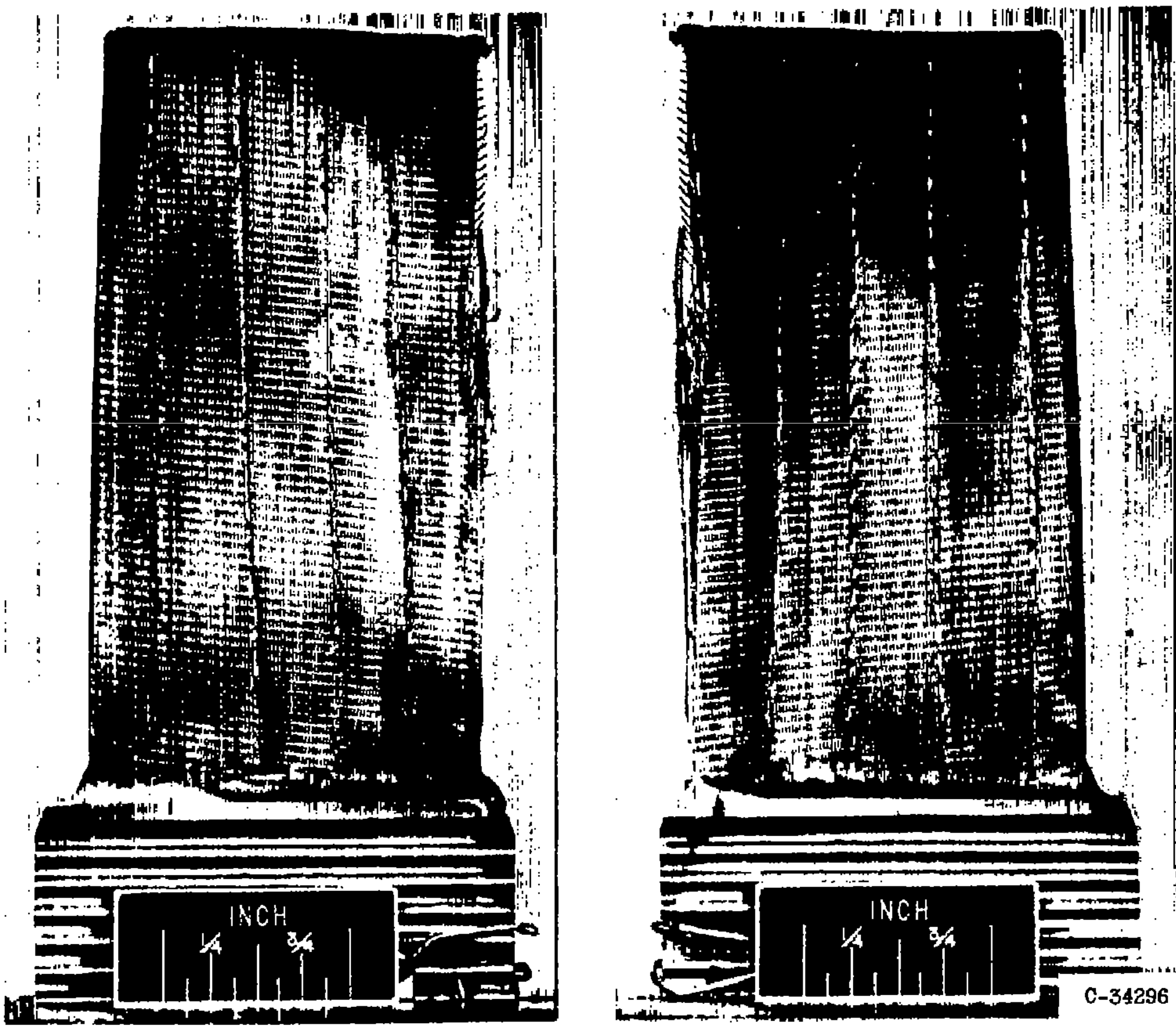
Figure 6. - Variation of supporting-member temperature with engine speed and coolant flow, blade 1.



(a) Chordwise temperature distribution (blade 1).

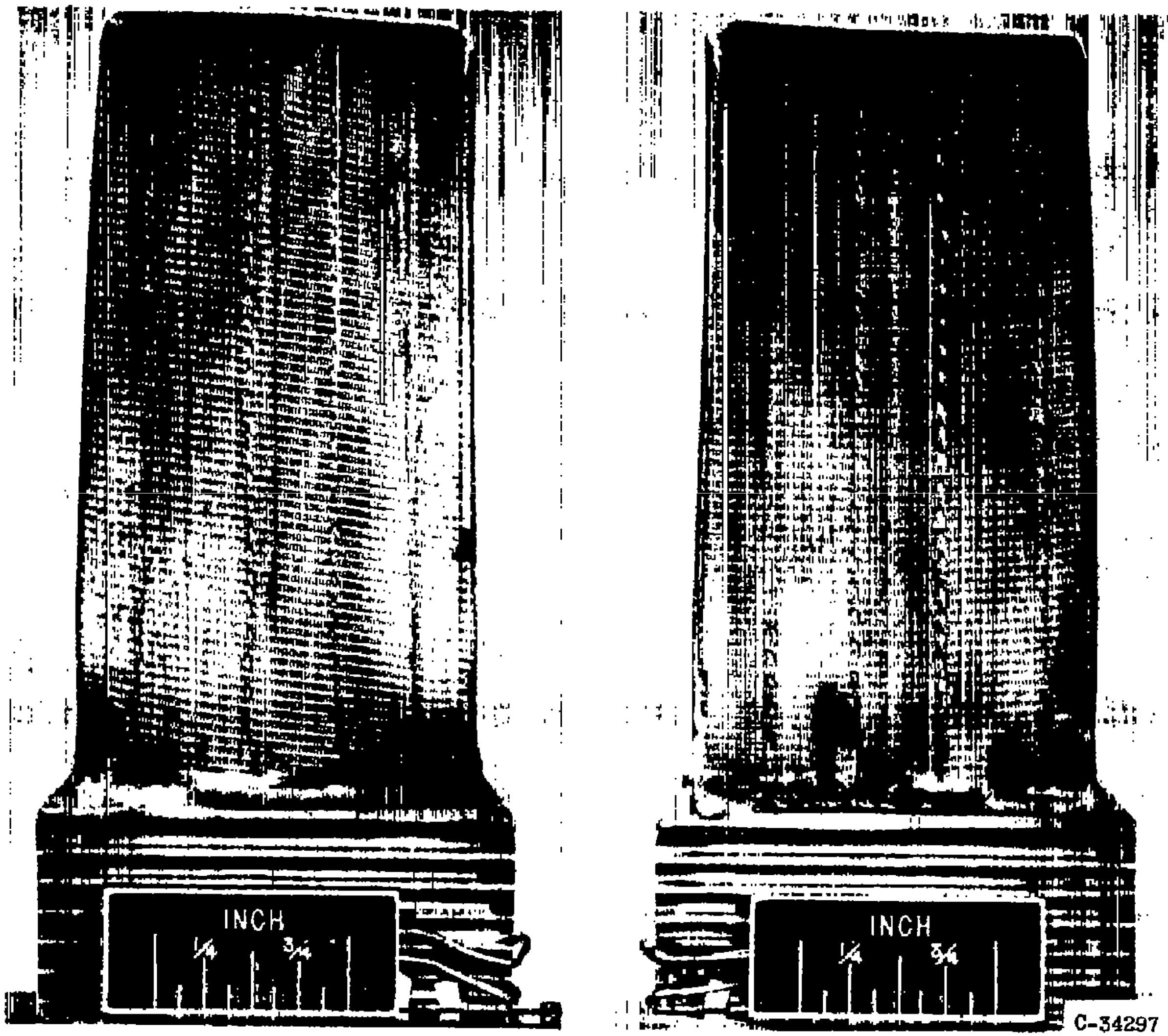
(b) Spanwise temperature distribution (blade 2).

Figure 7. - Typical strut temperatures for blade-tip speed of 1130 feet per second (10,000 rpm) and effective gas temperature of 1135° F.



(a) Suction surface. (b) Pressure surface.

Figure 8. - Blade 1 after subjection to engine test.



(a) Suction surface.

(b) Pressure surface.

Figure 9. - Blade 2 after subjection to engine test.

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